

# Effective Compilation of Higher-Order Programs

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<https://github.com/AnyDSL/thorin>

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# Introduction

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imperative languages C, Fortran, ...

- instruction lists + CFGs
  - LLVM
  - GIMPLE (gcc)

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  - Java Hotspot
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**functional languages** Haskell, ML, ...

- $\lambda$ -calculus
  - Core (GHC)
  - Lambda IR (OCaml)
  - Continuation Passing Style (CPS) [Appel06]

## Motivation: Post-Order Visit

```
struct Node {
    int data;
    Node* left;
    Node* right;
};

void post_order_visit(Node* n) {
    if (n->left)
        post_order_visit(n->left, f);

    if (n->right)
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    cout << n->data << endl;
}
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## 1. Iterators

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## 1. Iterators

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## 2. Higher-order Functions

# Factor-out Visiting Algorithm

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void post_order_visit(Node* n, function<void(int)> f) {
    if (n->left)
        post_order_visit(n->left, f);

    if (n->right)
        post_order_visit(n->right, f);

    f(n->data);
}

void print(Node* n) {
    post_order_visit(n, [](int d) { cout << d << endl; });
}

void sum(Node* n) {
    int result = 0;
    post_order_visit(n, [&](int d) { result += d; });
    cout << result << endl;
}
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# Compiling

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        post_order_visit(n->left, f);

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}

void print(Node* n) {
    post_order_visit(n, [](int d) { cout << d << endl; });
}
```

clang -O3 -fno-exceptions



# print with clang -O3 -fno-exceptions

```
define void @_Z1printNode(struct.Node* nocapture readonly %0) #3 {
entry:
  %tmp = alloca %"class.std::function", align 8
  %_M_manager.i = getelementptr inbounds %"class.std::function", %"class.std::function"* %tmp, i64 0, i32 0, i32 1
  %_M_widen.i = getelementptr inbounds %"class.std::function", %"class.std::function"* %tmp, i64 0, i32 1
  store void @N"union.std::Any_data", i32* @_Z1217_function_handlerFv12Z1printNodeIS3_363_M_invokeDRS49_Any_data01, void @N"union.std::Any_data", i32** %_M_widen.i, align 8, i8aa 11
  store 1 @N"union.std::Any_data", %"union.std::Any_data", i32* @_Z1216_function_baseI12Z1printNodeIS3_363_M_managerDRS49_Any_dataDRS5_S18_Manager_operation1, 1 @N"union.std::Any_data",
  %union.std::Any_data", i32** %_M_manager.i, align 8, i8aa 16
  call fastcc void @_Z1866_base_construct(struct.Node* %0, %"class.std::function"* nonnull %tmp)
  %0 = load 1 @N"union.std::Any_data", %"union.std::Any_data", i32* @_Z1217_function_baseI12Z1printNodeIS3_363_M_manager.i, align 8, i8aa 16
  %tbody.1 = cmp eq 1 @N"union.std::Any_data", %"union.std::Any_data", i32* %0, null
  br if %tbody.1, label %_Z1216_function_baseI12Z1printNodeIS3_363_M_manager.i, label %if.then.1

if.then.1:
  %prds = %entry
  %_M_factor.i = getelementptr inbounds %"class.std::function", %"class.std::function"* %tmp, i64 0, i32 0, i32 0
  %call.i = call noexcept @N"union.std::Any_data" @dereferenceable(16) %_M_factor.i, %"union.std::Any_data" @dereferenceable(16) %_M_factor.i, i32* %0
  br label %_Z1216_function_baseI12Z1printNodeIS3_363_M_manager.i

_Z1216_function_baseI12Z1printNodeIS3_363_M_manager.i.exit:
  %prds = %entry, %if.then.1
}

define internal void @_Z1217_function_handlerFv12Z1printNodeIS3_363_M_invokeDRS49_Any_data01@N"union.std::Any_data" nocapture readonly dereferenceable(16) %_factor, i32* nocapture readonly dereferenceable(4) %_args) #3 align 2 {
entry:
  %0 = load i32, i32** %_args, align 4, i8aa 114
  %call.i = tail call @dereferenceable(272) @"class.std::basic_ostream" @_Z12616N"class.std::basic_ostream" nonnull @_Z126out, i32 %0, i32 %2
  %0 = bitcast %"class.std::basic_ostream" %call.i to i8**
  %variable.i.i = load i8*, i8** %0, align 8, i8aa 115
  %tbody.offset.i.i = getelementptr @_184, %variable.i.i, i64 -24
  %0 = bitcast i8* %tbody.offset.i.i to i64*
  %tbody.offset.i.i = load i64, i64** %0, align 8
  %0 = bitcast %"class.std::basic_ostream" %call.i to i8*
  %tbody.ptr.i.i = getelementptr inbounds i8, i8** %0, i64 %tbody.offset.i.i
  %_M_type.i.i = getelementptr inbounds i8, i8* %tbody.ptr.i.i, i64 240
  %0 = bitcast i8* %_M_type.i.i to %"class.std::ctype**"
  %0 = load %"class.std::ctype**", %"class.std::ctype**" %0, align 8, i8aa 117
  %tbody.15.i.i = cmp eq %"class.std::ctype**" %0, null
  br if %tbody.15.i.i, label %if.then.16.i, label %_Z1213_check_facetIS1ctypeISERKT_P52, exit

if.then.16.i:
  tail call void @_Z1216_throw_bad_cast() #7
  unreachable

_Z1213_check_facetIS1ctypeISERKT_P52, exit.i:
  %prds = %entry
  %_M_widen.i.i = getelementptr inbounds %"class.std::ctype", %"class.std::ctype"* %0, i64 0, i32 8
  %0 = load i8, i8** %_M_widen.i.i, align 8, i8aa 120
  %tbody.1.i.i = cmp eq i8 %0, 0
  br if %tbody.1.i.i, label %if.end.i.i, label %if.then.i.i

if.then.i.i:
  %prds = %_Z1213_check_facetIS1ctypeISERKT_P52, exit.i
  %arrayptr.i.i = getelementptr inbounds %"class.std::ctype", %"class.std::ctype"* %0, i64 0, i32 9, i64 10
  %0 = load i8, i8** %arrayptr.i.i, align 1, i8aa 122
  br label %*_Z121printNodeIS3_363_M_manager.i

if.end.i.i:
  %prds = %_Z1213_check_facetIS1ctypeISERKT_P52, exit.i
  tail call void @_Z1245ctypeIS13_M_widen_i16N"class.std::ctype"* nonnull %0) #2
  %0 = bitcast %"class.std::ctype"* %0 to i8 [%"class.std::ctype**", i8**]
  %tbody.13.i.i = load i8 [%"class.std::ctype**", i8**], i8 [%"class.std::ctype**", i8**] %0, align 8, i8aa 115
  %tbody.1.i.i = getelementptr inbounds i8 [%"class.std::ctype**", i8**], i8 [%"class.std::ctype**", i8**] %tbody.13.i.i, i64 6
  %0 = load i8 [%"class.std::ctype**", i8**], i8 [%"class.std::ctype**", i8**] %tbody.1.i.i, align 8
  %call.14.i.i = tail call @sigext 18 %0 [%"class.std::ctype**" nonnull %0, i8 @sigext 10] #2
  br label %*_Z121printNodeIS3_363_M_manager.i

*_Z121printNodeIS3_363_M_manager.i.exit:
  %prds = %if.then.i.i, %if.end.i.i
  %retval.0.i.i = phi i8 [%0, %if.then.i.i], [%call.14.i.i, %if.end.i.i]
  %call.i.i = tail call @dereferenceable(272) @"class.std::basic_ostream" @_Z12616N"class.std::basic_ostream" nonnull %call.i, i8 @sigext %retval.0.i.i) #2
  %call.i.i = tail call @dereferenceable(272) @"class.std::basic_ostream" @_Z12616N"class.std::basic_ostream" nonnull %call.i.i) #2
}

define internal noinline @_Z1216_function_baseI12Z1printNodeIS3_363_M_managerDRS49_Any_dataDRS5_S18_Manager_operation1@N"union.std::Any_data" nocapture dereferenceable(16) %_dest,
dereferenceable(16) %_source, i32 %_op) #5 align 2 {
entry:
  switch i32 %_op, label %no_epilog [
    i32 0, label %no
    i32 1, label %no_bbl
  ]

no:
  %prds = %entry
  %0 = bitcast %"union.std::Any_data" %_dest to %"class.std::type_info**"
  store %"class.std::type_info**" @bitcast ([i8*, i8**] @_Z1212printNodeIS3_363_M_manager.i, %"class.std::type_info**"), %"class.std::type_info**" %0, align 8, i8aa 111
  br label %no_epilog

no_bbl:
  %prds = %entry
  %0 = bitcast %"union.std::Any_data" %_dest to %"union.std::Any_data**"
  store %"union.std::Any_data**" @N"source", %"union.std::Any_data**" %0, align 8, i8aa 111
  br label %no_epilog

no_epilog:
  %prds = %entry, %no_bbl, %no
}

ret void
}
```

- *A Graph-Based Higher-Order Intermediate Representation*  
Leißa, Köster, and Hack.  
CGO 2015

- *A Graph-Based Higher-Order Intermediate Representation*  
Leißa, Köster, and Hack.  
CGO 2015
- *Shallow Embedding of DSLs via Online Partial Evaluation*  
Leißa, Boesche, Hack, Membarth, and Slusallek.  
GPCE 2015.

# Closure Conversion

---



# Closure Conversion

```
void range(int a, int b,  
           function<void(int)> f)  
{  
    if (a < b) {  
        f(a);  
        range(a+1, b, f);  
    }  
}  
  
void foo(int n) {  
    range(0, n, [=] (int i) {  
        use(i, n);  
    });  
}
```

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```

```
struct closurebase {
    void (*f)(void* c, int i);
};

struct closure {
    closurebase base;
    int n;
};

void lambda(void* c, int i) {
    use(i, (closure* c)->n);
}

void range(int a, int b, void* c) {
    if (a < b) {
        ((closurebase*) c)->f(c, a);
        range(a+1, b, c);
    }
}

void foo(int n) {
    closure c = {{&lambda}, n};
    range(0, n, &c);
}
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struct closure {
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void lambda(void* c, int i) {
    use(i, (closure* c)->n);
}

void range(int a, int b, void* c) {
    if (a < b) {
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struct closurebase {
    void (*f)(void* c, int i);
};

struct closure {
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void lambda(void* c, int i) {
    use(i, (closure* c)->n);
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void range(int a, int b, void* c) {
    if (a < b) {
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void foo(int n) {
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# Closure Conversion

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  - `range`
  - `post_order_visit`

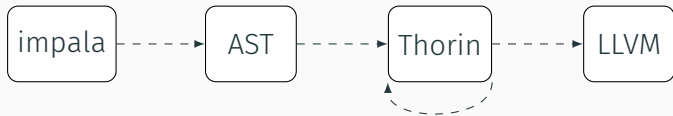
# Closure Conversion



- reimplement for every front-end
- taints the IR with **implementation** of higher-order functions
  - bloats the IR
  - set of finely tuned analyses & transformations needed for optimization



# Closure Conversion



- Thorin = higher-order + CPS + "sea of nodes"
- directly translate higher-order functions and calls to Thorin
- keep higher-order functions till late during compilation
- powerful closure-elimination phase

Thorin

---

```
int foo(int n) {  
    int a;  
    if (n==0) {  
        a = 23;  
    } else {  
        a = 42;  
    }  
  
    return a;  
}
```

# SSA-Form

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int foo(int n) {  
    int a;  
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    }  
  
    return a;  
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```

```

foo(n: int, ret: int  $\rightarrow$   $\perp$ )  $\rightarrow$   $\perp$ :
  let
    then()  $\rightarrow$   $\perp$ :
      next(23)
    else()  $\rightarrow$   $\perp$ :
      next(42)
  next(a: int)  $\rightarrow$   $\perp$ :
    ret(a)
  in
    branch(n==0, then, else)

```

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foo(n: int, ret: int → ⊥) → ⊥:  
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# Classic CPS vs Thorin

Classic CPS

Thorin

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Classic CPS	Thorin
let	graph edge ( <b>acyclic</b> graph)
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# Classic CPS vs Thorin

Classic CPS	Thorin
let	graph edge ( <b>acyclic</b> graph)
letrec	graph edge ( <b>cyclic</b> graph)
block nesting	implicit
name resolution	graph edge
name capture	-

# SSA vs Thorin

```
int foo(int n) {  
    branch(n==0, then, else)  
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parameter

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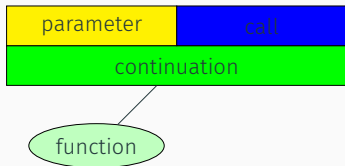
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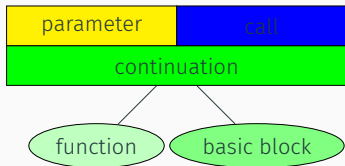
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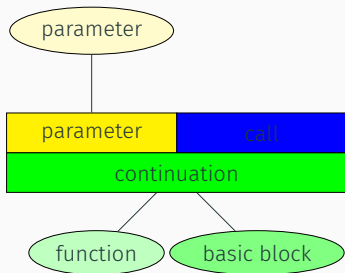
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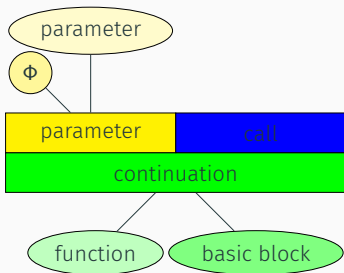
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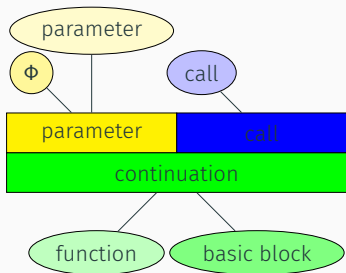
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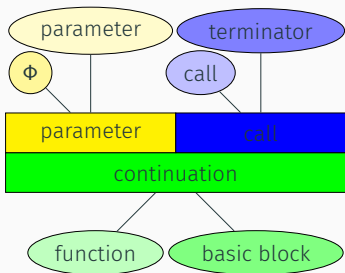
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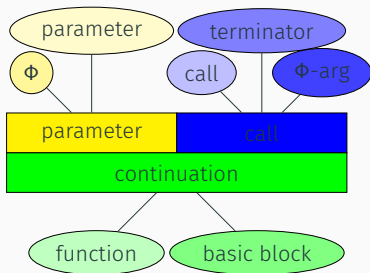
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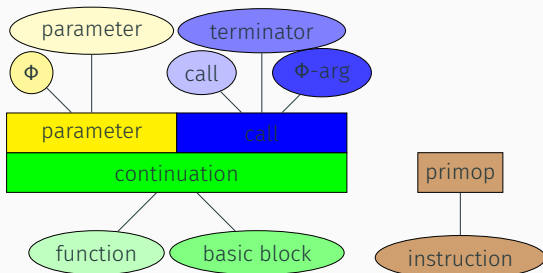




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# Lambda Mangling

---

## Control-Flow Form

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- 
- Thorin program in CFF if
    - first-order continuation  $\Rightarrow$  basic block
    - top-level, continuation with “return”  $\Rightarrow$  function
  - straightforward to translate to SSA form [Kelsey95]
  - no closures needed

# Not in CFF

```
void range(int a, int b, function<void(int)> f) {  
    //...  
    range(a+1, b, f);  
}
```

```
range(a: int, b: int, f: cn(int, cn()), ret: cn()):  
    /*  
     * ...  
     */  
    range(a+1, b, f, ret)
```

---

CFF-convertible if

- recursion-free or
- tail-recursive

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CFF-convertible if

- recursion-free or
- tail-recursive

# Not in CFF

```
void range(int a, int b, function<void(int)> f) {  
    //...  
    range(a+1, b, f);  
}
```

```
range(a: int, b: int, f: cn(int, cn()), ret: cn()):  
    /*  
     * ...  
     */  
    range(a+1, b, f, ret)
```

---

CFF-convertible if

- recursion-free or
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void range(int a, int b, function<void(int)> f) {  
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```

---

CFF-convertible if

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# Not in CFF

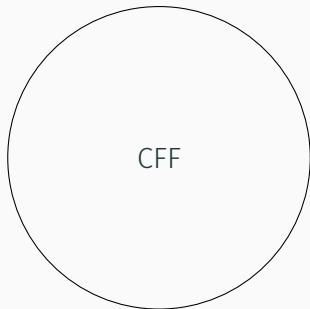
```
void range(int a, int b, function<void(int)> f) {  
    //...  
    range(a+1, b, f);  
}
```

```
range(a: int, b: int, f: cn(int, cn()), ret: cn()):  
    /*  
     * ...  
     */  
    range(a+1, b, f, ret)
```

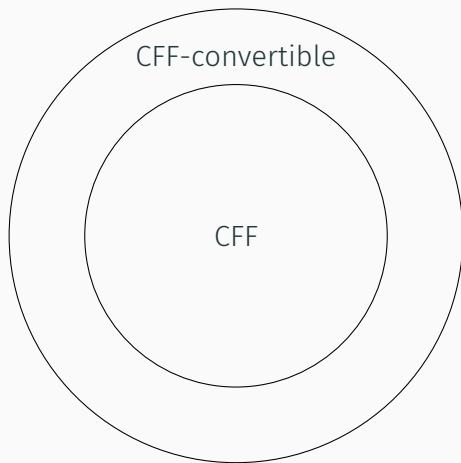
---

CFF-convertible if

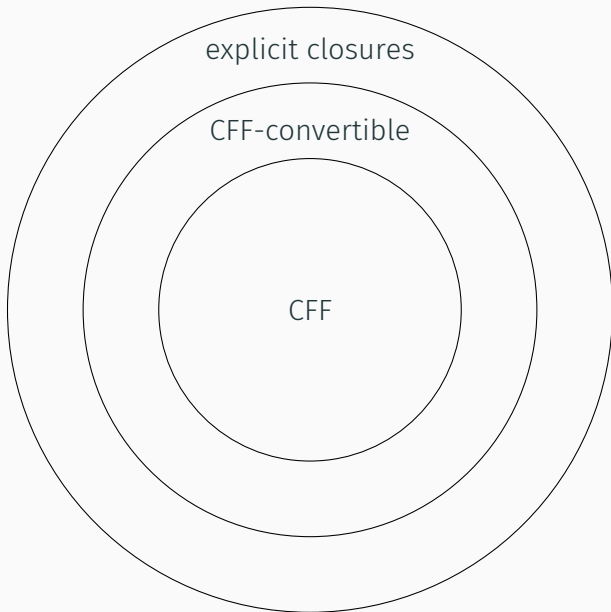
- recursion-free or
- tail-recursive



# Classes of Thorin Programs

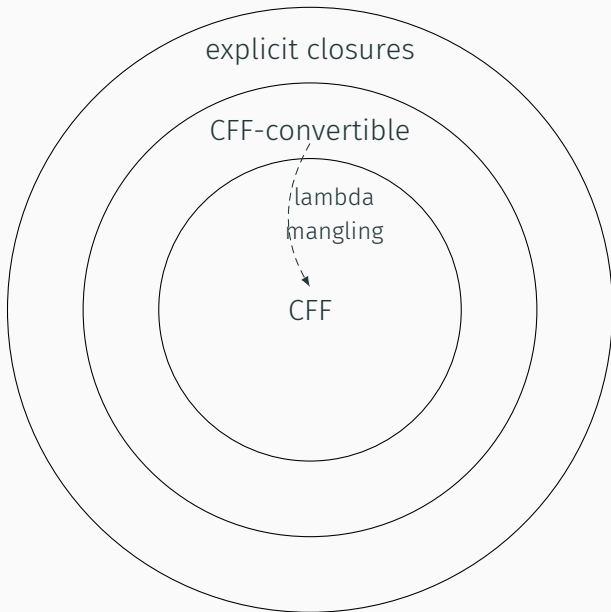


# Classes of Thorin Programs





# Classes of Thorin Programs



## Lambda Mangling = partial inlining/outlining

- (partial) inlining
- (partial) outlining

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- (partial) inlining
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- clone basic blocks/functions

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- loop peeling
- loop unrolling

## Lambda Mangling = partial inlining/outlining

- (partial) inlining
- (partial) outlining
- clone basic blocks/functions
- loop peeling
- loop unrolling
- tail-recursion elimination
- ...

Impala

---

```
fn post_order_visit(n: &Node, f: fn(int) -> ()) -> () {
    if n.left != nil {
        post_order_visit(n.left, f);
    }
    if n.right != nil {
        post_order_visit(n.right, f);
    }
    f(n.data)
}

fn print(n: &Node) -> () {
    post_order_visit(n, |d| {
        println(d);
    });
}
```

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fn post_order_visit(n: &Node, f: fn(int) -> ()) -> () {
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fn print(n: &Node) -> () {
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}

fn print(n: &Node) -> () {
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        println(d);
    });
}
```

## Impala - `for` Syntax

```
fn post_order_visit(n: &Node, f: fn(int) -> ()) -> () {
    if n.left != nil {
        post_order_visit(n.left, f);
    }
    if n.right != nil {
        post_order_visit(n.right, f);
    }
    f(n.data)
}

fn print(n: &Node) -> () {
    for d in post_order_visit(n) {
        println(d);
    }
}
```

## Impala - sum

```
fn sum(n: &Node) -> () {  
    let mut result = 0;  
  
    for d in post_order_visit(n) {  
        result += d  
    }  
  
    println(result);  
}
```



## Impala - sum

```
fn sum(n: &Node) -> () {  
    let mut result = 0;  
  
    for d in post_order_visit(n) {  
        result += d  
    }  
  
    println(result);  
}
```

## Impala - sum

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fn sum(n: &Node) -> () {  
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    for d in post_order_visit(n) {  
        result += d  
    }  
  
    println(result);  
}
```

## Impala - `return` is the new `continue`

```
fn sum(n: &Node) -> () {  
    let mut result = 0;  
  
    post_order_visit(n, |d| {  
        if d == 23 {  
            return()  
        }  
        result += d  
    })  
  
    println(result);  
}
```

## Impala - `return` is the new `continue`

```
fn sum(n: &Node) -> () {
    let mut result = 0;

    post_order_visit(n, |d| {
        if d == 23 {
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        result += d
    })

    println(result);
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            return()  
        }  
        result += d  
    })  
  
    println(result);  
}
```

## Impala - `continue` is the new `return`

```
fn sum(n: &Node) -> () {
    let mut result = 0;

    for d in post_order_visit(n) {
        if d == 23 {
            continue()
        }
        result += d
    }

    println(result);
}
```

## Impala - Give me a **break**, please!

```
fn sum(n: &Node) -> () {
    let mut result = 0;

    for d in post_order_visit(n) {
        if d == 23 {
            break()
        }
        result += d
    }

    println(result);
}
```



```
fn post_order_visit(n: &Node, f: fn(int) -> ()) -> () {
    if n.left != nil {
        post_order_visit(n.left, f);
    }
    if n.right != nil {
        post_order_visit(n.right, f);
    }
    f(n.data)
}

fn print(n: &Node) -> () {
    for d in post_order_visit(n) {
        println(result);
    }
}
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fn print(n: &Node) -> () {
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    }
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    }
    f(n.data)
}

fn print(n: &Node) -> () {
    for d in post_order_visit(n) {
        println(result);
    }
}
```

## Generated LLVM (1)

```
define internal void @post_order_visit_392(%Node* %n_394) {
post_order_visit_392_start:
    br label %post_order_visit

post_order_visit:
    %0 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 1
    %1 = load %Node*, %Node** %0
    %2 = icmp ne %Node* %1, null
    br i1 %2, label %if_then, label %if_else

if_then:
    call void @post_order_visit_392(%Node* %1)
    br label %next

if_else:
    br label %next
; ...
```

## Generated LLVM (1)

```
define internal void @post_order_visit_392(%Node* %n_394) {
post_order_visit_392_start:
    br label %post_order_visit

post_order_visit:
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    br i1 %2, label %if_then, label %if_else

if_then:
    call void @post_order_visit_392(%Node* %1)
    br label %next

if_else:
    br label %next
; ...
```

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if_then:
    call void @post_order_visit_392(%Node* %1)
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if_else:
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```

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  %2 = icmp ne %Node* %1, null
  br i1 %2, label %if_then, label %if_else

if_then:
  call void @post_order_visit_392(%Node* %1)
  br label %next

if_else:
  br label %next
; ...
```

## Generated LLVM (2)

```
; ...
next:
  %3 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 2
  %4 = load %Node*, %Node** %3
  %5 = icmp ne %Node* %4, null
  br i1 %5, label %if_then2, label %if_else1

if_then2:
  call void @post_order_visit_392(%Node* %4)
  br label %next3

if_else1:
  br label %next3

next3:
  %6 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 0
  %7 = load i32, i32* %6
  call void @println(i32 %7)
  ret void
}
```



## Generated LLVM (2)

```
; ...
next:
  %3 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 2
  %4 = load %Node*, %Node** %3
  %5 = icmp ne %Node* %4, null
  br i1 %5, label %if_then2, label %if_else1

if_then2:
  call void @post_order_visit_392(%Node* %4)
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if_else1:
  br label %next3

next3:
  %6 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 0
  %7 = load i32, i32* %6
  call void @println(i32 %7)
  ret void
}
```

## Generated LLVM (2)

```
; ...
next:
  %3 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 2
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next3:
  %6 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 0
  %7 = load i32, i32* %6
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}
```

## Generated LLVM (2)

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; ...
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}
```

## Generated LLVM (2)

```
; ...
next:
  %3 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 2
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  %6 = getelementptr inbounds %0, %Node* %n_394, i32 0, i32 0
  %7 = load i32, i32* %6
  call void @println(i32 %7)
  ret void
}
```

# Evaluation

---

# Benchmarks – The Computer Language Benchmark Game<sup>1</sup>

	runtime in ms	
	C	Impala
aobench	1.220	1.357
fannkuch-redux	27.137	28.070
fasta	2.313	1.517
mandelbrot	2.143	2.113
meteor-contest	0.047	0.043
n-body	5.497	6.130
pidigits	0.710	0.763
regex	6.477	6.470
reverse-complement	1.090	1.220
spectral-norm	4.423	4.480

<sup>1</sup><https://benchmarksgame.alioth.debian.org/>

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- high-order IR does not “hurt” performance
- all closures removed

---

<sup>1</sup><https://benchmarksgame.alioth.debian.org/>

## Summary

---



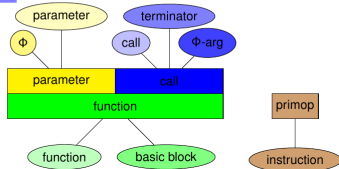
# Conclusions

```
foo(n: int, rat: fn(int)):  
  n=0  
  branch(•, then, else)  
  
then():  
  next(23)  
  
else():  
  next(42)  
  
next(a: int):  
  rat(a)
```

# Conclusions

```
foo(n: int, ret: fn(int)):  
  n:=0  
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then():  
  next(23)  
  
else():  
  next(42)  
  
next(a: int):  
  ret(a)
```

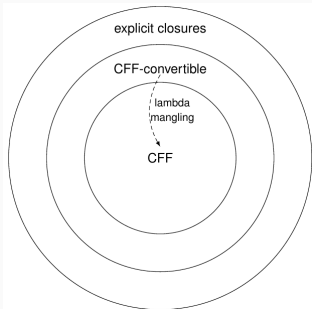
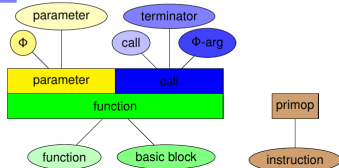
```
int foo(int n) {  
  branch(n==0, then, else)  
then:  
  goto next;  
else:  
  goto next;  
next:  
  int a = φ(23 [then], 42 [else]);  
  return a;  
}  
  
foo(n: int, ret: fn(int)):  
  branch(n==0, then, else)  
then():  
  next(23)  
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# Conclusions

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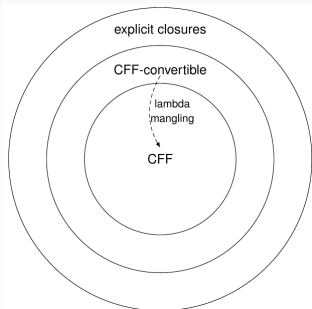
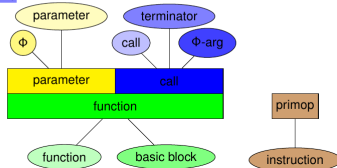
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  branch(n==0, then, else)  
then:  
  goto next;  
else:  
  goto next;  
next:  
  int a = φ(23 [then], 42 [else]);  
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# Conclusions

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```



Thank you!  
Questions?